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Functional Interface Considerations within an Exploration Life Support System Architecture

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As notional life support system (LSS) architectures are developed and evaluated, myriad options must be considered pertaining to process technologies, components, and equipment assemblies. Each option must be evaluated relative to its impact on key functional interfaces within the LSS architecture. A leading notional architecture has been developed to guide the path toward realizing future crewed space exploration goals. This architecture includes atmosphere revitalization, water recovery and management, and environmental monitoring subsystems. Guiding requirements for developing this architecture are summarized and important interfaces within the architecture are discussed. The role of environmental monitoring within the architecture is described.

Nomenclature

AR	=	atmosphere revitalization
C&DH	=	command and data handling
EM	=	environmental monitoring
EVA	=	extravehicular activity
FOM	=	figure of merit
ISS	=	International Space Station
LSS	=	life support system
NASA	=	National Aeronautics and Space Administration
NTRS	=	NASA Technical Reports Server
ORU	=	on-orbit replaceable unit
SMAC	=	spacecraft maximum allowable concentration
SWEG	=	spacecraft water exposure guidelines
VDC	=	volts direct current
WMS	=	waste management system
WRM	=	water recovery and management
C	=	Celsius
m	=	meter
kg	=	kilogram
kPa	=	kilopascal
kW	=	kilowatt
psia	=	pounds per square inch absolute

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I. Introduction

DEVELOPING and studying mission architectures that implement the United States' National Space Policy toward a capability-driven framework that extends the horizon of space exploration beyond the moon toward Mars requires unique, enabling technological capabilities.[1-4] Among these capabilities is a regenerative, closed-loop life support system (LSS) that can support a crew of four, with the capability to grow to six, for missions lasting 500 to 1000 days and include deep space transit periods ranging between 420 days and 620 days.[5-7] Consisting of atmosphere revitalization (AR), water recovery and management (WRM), and environmental monitoring (EM) subsystems as depicted by Fig. 1, the notional LSS architecture under development to support future exploration missions is building upon the core process technologies and significant in-flight operational record of the LSS used aboard the International Space Station (ISS).[8-10] Ongoing technological development seeks to address functional needs and technical gaps that exist between the ISS and future exploration missions as well as serve to accelerate Phase A in a future exploration program life cycle.[11-15]

Taking advantage of the ISS as a laboratory that provides the unique conditions of a long duration, sealed living environment provides a rare resource for future LSS development. The environment aboard the ISS allows for LSS equipment interactions with that environment to be observed, studied, understood, and factored into the next generation system while operational strategies suitable for exploration missions can be tested. Observations and lessons learned from over three decades of design, development, testing, in-flight operations, refinement, and international collaboration that has culminated in the contemporary LSS aboard the ISS are invaluable for pre-Phase A developmental efforts. As the exploration LSS developmental efforts make progress toward Phase A development, these insights will prove invaluable to expediting the exploration mission program's life cycle.[16]

Each functional area depicted in Fig. 1 represents a top level trade space for technological development. Lower level trade spaces for each developmental area must occur within a framework of guiding requirements. The technical solutions must also seamlessly address functional interfaces. The following discussion summarizes guidance relating to functional requirements and interfaces within the notional architecture.

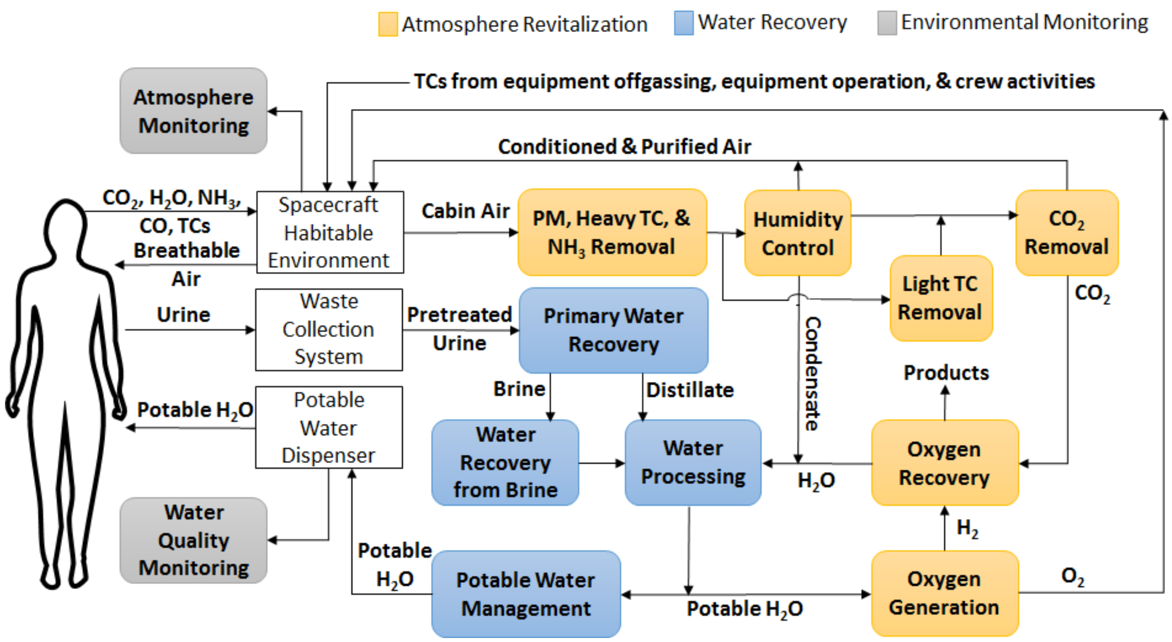

Figure 1. A life support system functional architecture for exploration missions.

II. Guiding Requirements for an Exploration Life Support System

Guiding functional requirements are essential for developing a notional LSS architecture and selecting suitable improvements in core process technologies relative to the ISS as the starting basis. At the present stage in the developmental life cycle, the guiding requirements that describe the basic mission, define general performance objectives, and provide design insight are derived from many source documents. Ultimately these guiding requirements will form the basis for future exploration program system requirements. The following describes the contribution of various documents to the exploration LSS guiding requirements.

A. Mission Definition Guidance

Information regarding the exploration mission duration and crew size is useful for selecting core process technologies and conducting early component sizing evaluations. The Mars Design Reference Mission serves as the basis for this information. The crew of four on a mission lasting at least 500 days and up to 1000 days is the foundation for exploration LSS development and part of the capability-driven framework for exploration. As well, this documentation provides guidance on the deep space habitat pressurized volume of ~280 m^3 which is to provide ~24 m^3 habitable volume per crewmember.[17]

B. Performance Objective Guidance

With the guidance on the crew size and mission duration, more details on metabolic loads and demands are found in the National Aeronautics and Space Administration's (NASA) technical standards and handbooks. The NASA Space Flight Human System Standard and the Human Integration Design Handbook are excellent sources for guiding the LSS design point for metabolic loads and demands.[18, 19] The NASA Space Flight Human System Standard references two documents that provide details on specific cabin atmospheric quality and potable water quality provide functional performance goals. These two documents, JSC 20584 and JSC 63414, provide details on the spacecraft maximum allowable concentrations (SMAC) for airborne trace contaminants and spacecraft water exposure guidelines (SWEG), respectively. [20, 21] Recent developments pertaining to the need to control the carbon dioxide partial pressure to levels well below the published SMAC are considered as a functional goal.[22] The guidance on cabin atmospheric pressure provided by the NASA technical standards and handbooks has been supplemented by recommendations by the NASA Exploration Atmospheres Working Group which recommended 101.5 kPa (14.7 psia) and 21% oxygen partial pressure for exploration mission design.[23] An update in 2013 retained the 101.5 kPa and 21% oxygen partial pressure design point for deep space exploration missions such as Mars transit but included the allowance for mission architectures with high-frequency extravehicular activity (EVA) demands to have the capability to operate at 56.5 kPa (8.2 psia) and 34% oxygen partial pressure. Exploration LSS developmental efforts have been working within the 101.5 kPa and 21% oxygen partial pressure guidance.

C. Supplemental Guidance

The mission definition guidance and performance objective requirements are supplemented by insight provided by subject matter expertise, flight program observations and lessons learned, and how programs such as ISS and Constellation have implemented these requirements in their specific program specification and requirement documents. Excellent supplemental guidance can be found in Guidelines and Capabilities for Designing Human Missions and the Constellation Human-Systems Integration Requirements document.[24, 25] NASA technical publications available via the NASA Technical Reports Server (NTRS) are also excellent supplemental sources. Observations and lessons learned from the ISS program are documented in numerous conference publications that describe LSS status and assembly level performance. The bibliography contains a listing of helpful supplementary documentation suitable for top-level LSS design development.

III. System Functional and Physical Interface Overview

The interfaces that exist between a crewed spacecraft and the LSS are numerous and can be quite complex. Figure 2 provides an extensive interface diagram for the notional LSS architecture. Significant interfaces between the LSS and the crew and the vehicle's structural, command and data handling (C&DH), electrical power, thermal control, logistics management, and EVA systems are evident on examining Fig. 2. Specialty engineering considerations can drive requirements for acoustic noise, materials and processes, and maintainability among other specialty areas. Identifying all of the interfaces an LSS may have requires iteration and a high degree of communication across multiple technical disciplines. These iterative communications to define requirements is challenging and time consuming. Figure 2 represents a preliminary effort to evaluate primary interfaces.

Simplifying the interface diagram to consider the LSS alone is helpful for bounding the challenge. Figure 3 shows a simplified interface diagram for the LSS and its primary subsystems. In Fig. 3 the primary resources such as atmospheric gases and water are considered along with power distribution, thermal control, and C&DH.

Between the three LSS subsystems, the most significant interface consists of transferring water from the WRM subsystem to the AR subsystem to generate oxygen as illustrated by both Figs. 1 and 3. This water transfer represents a significant water demand for an exploration mission. Therefore, it is desirable to reduce the AR subsystem's net water demand by employing carbon dioxide reduction. Depending on the carbon dioxide reduction technique selected, a fraction of the AR subsystem's water demand ranging between 50% and 90% can be returned to the WRM subsystem. Therefore, selecting a carbon dioxide reduction technique that can minimize the water demands

Spacecraft	Habitable volume; infrastructure; top level requirements; volume and mass properties allocations	Chemical contaminant offgassing; natural and induced environments - temperature, pressure, vibration, etc.	Top level structural requirements; vibration & loads; volume and mass properties allocations	Commands from crew and/or control center; automation requirements	Top level electrical power requirements	Natural & induced thermal environmental loads; top level thermal control requirements	Volume for equipment storage; O_2, N_2, H_2O supplies; food, crew kits; volume and mass properties allocations	Airlock; volume and mass properties allocations	Speciality engineering lop level requirements
Resource & logistics demands	Crew & Crew Systems	CO_2, moisture, & chemical and particulate contaminants; exercise loads	Crew structural interfaces	System telemetry & communications	Electrical power demand	Rejected thermal energy	Limited life items, maintainability & reliability data	Crew & crew systems requirements	Materials lists, limited life items, maintainability source data, etc.
Resource distribution & logistics demands; mass, power, & volume needs	O_2, potable H_2O, cabin pressure & composition management; crew preference item LSS compatibility	Life Support System	Equipment mass loads; structurally-borne vibration loads	System telemetry & status; resource usage rate data	Electrical power demand	Rejected thermal energy; requirements for working fluid LSS compatibility	Limited life items, maintainability & reliability data	O_2 for tanks; potable water; dust intrusion barrier effectiveness requirements	Materials lists, limited life items, maintainability source data, etc.
Requirements for center of gravity; requirements for stuctural connection points	Structural connections & physical layout	Structural connections & physical layout; fracture criticality requirements	Structural & Mechanisms	System telemetry & status	Electrical power demand	Rejected thermal energy	Limited life items, maintainability & reliability data	Airlock and dust intrusion barrier structures	Materials lists, limited life items, maintainability source data, etc.
System telemetry to control center; resource utilization status; software type; processor type	Mode configuration, commands, & software loads; software type; processor type	Mode configuration, commands, & software loads; software type; processor type	Mode configuration, commands, & software loads; software type; processor type	Command & Data Handling	Mode configuration, commands, & software loads	Rejected thermal energy	Resource usage rate data	Mode configuration, commands, & software loads; communication between IVA & EVA crew	Materials lists, limited life items, maintainability source data, etc.
Requirements for supporting electical power distribution	120 VDC power bus	120 VDC power bus	120 VDC power bus	System telemetry & status; 120 VDC power bus	Electrical Power	Rejected thermal energy; 120 VDC power bus	Limited life items, maintainability & reliability data	120 VDC power bus	Materials lists, limited life items, maintainability source data, etc.
Requirements for supporting thermal control	Coolant to equipment and cold plates	Coolant to equipment and cold plates	Coolant to equipment an cold plates; Conducted thermal energy	Coolant to equipment and cold plates	Coolant to equipment and cold plates	Thermal & Environmental Control	Limited life items, maintainability & reliability data	Thermal coolant	Materials lists, limited life items, maintainability source data, etc.
Requirements for supporing logistics, including maintainability	Food, crew kits	Spare parts, H_2O makup, N_2, O_2 backup	Spare parts & tools	Spare parts & tools	Spare parts & tools	Spare parts; coolant makeup	Logistics Management	Spare parts & tools	Materials lists, limited life items, maintainability source data, etc.
Requirements supporting EVA operations	Crew interfaces	Collected CO_2	Structural architecture & loads	System telemetry, status, & communications	Power loads	Thermal loads	Maintainability & reliability data	EVA Systems	H_2O & O_2 losses
Requirements supporting specialty engineering	Materials, acoustics, maintainability requirements	Materials, acoustics, maintainability requirements	Materials and manufacturing requirements	Materials and maintainability requirements	Materials and maintainability requirements	Materials, acoustics, maintainability requirements	Materials and maintainability requirements	Materials, acoustics, maintainability requirements	Speciality Engineering - Acoustics, Materials & Processes, Maintainability, etc.

Figure 2. A detailed interface diagram showing interfaces between the LSS and vehicle systems. *Interfaces flow clockwise around the diagonal. Inputs are above the diagonal and outputs are below the diagonal.*

for the exploration destination is an important consideration for the LSS architecture. The potable water quality measured by the EM subsystem is important to reliable oxygen generation over the mission's duration; therefore, specific feed water quality requirements must be determined to provide the necessary reliability. Product water quality produced by carbon dioxide reduction processes must also be considered for its contaminant load on the WRM subsystem's water processing equipment. The following presents interfaces within each LSS subsystem.

A. Atmosphere Revitalization Subsystem Interfaces

The AR subsystem purifies the cabin atmosphere, maintains its composition within the parameters discussed in Section II, and recovers oxygen from carbon dioxide. As shown by Fig. 4, the AR subsystem consists of eight primary functional areas. These functional areas are the following:

1) Process gas moisture management.
2) Carbon dioxide removal.
3) Carbon dioxide conditioning and management.
4) Carbon dioxide reduction.
5) Carbon dioxide reduction product processing and management.
6) Oxygen generation and supply management.
7) Trace contaminant control.
8) Particulate matter and biocontaminant control.

The AR subsystem receives process air from the cabin ventilation system, purifies it, and returns

Spacecraft/Crew Inputs & Outputs	Electrical power; thermal control; makeup O_2, N_2, H_2O; structural; commands; logistics; maintenance	Provide interfaces with cabin ventilation system		
Potable H_2O, breathable atmosphere, environmental & system status, reject heat, respond to commands	Life Support System	Distribute process air to ARS, coordinate C&DH, electrical power, & thermal control	Distribute humidity condensate; urine, & wastewaters for processing	Supply atmospheric and potable water samples for analysis
	Generate O_2 (variable pressure)	Atmosphere Revitalization Subsystem	Provide H_2O from CO_2 reduction	Provide physical interfaces for monitoring instrumentation
	Provide potable H_2O for crew consumption	Provide potable H_2O for O_2 generation	Water Recovery & Management Subsystem	Provide physical interfaces for monitoring instrumenation
	Provide cabin atmospheric, potable water quality, and combustion product monitoring data	Provide cabin atmospheric monitoring data for control	Provide water quality data for control	Environmental Monitoring Subsystem

Figure 3. A simplified interface diagram for the LSS architecture.

it to the cabin. The purification processes remove particulate matter and biocontaminants, trace chemical contaminants, and carbon dioxide. The process air fed to the AR subsystem may need to be conditioned for temperature and moisture content to allow for the moisture management and carbon dioxide removal equipment function properly and optimize component sizes. It may also be necessary for the process air to pass through trace contaminant control and particulate matter control equipment before being delivered to the core atmosphere purification processing equipment which manages moisture and removes carbon dioxide. The AR subsystem also receives water from the WRM subsystem to produce oxygen. In return, the AR subsystem returns moisture removed from the process air stream to the cabin as well as returns water produced by the carbon dioxide reduction process to the WRM subsystem via the cabin humidity control equipment.

Figure 4 shows that the carbon dioxide reduction process is central to the overall AR subsystem architecture and has two internal interfaces. One with carbon dioxide removal and one with oxygen generation. These interfaces supply the carbon dioxide and hydrogen feed gases and require process control coordination. To ensure proper operation over the mission duration, the CO_2 and H_2 fed to the carbon dioxide reduction process must meet specified purities and moisture loads. An interface specification for feed gas purities and moisture load must be developed to facilitate AR subsystem integration. The coordinated operational protocols between carbon dioxide removal, carbon dioxide reduction, and oxygen generation process equipment must also be defined as part of the assembly-level interface requirements.

Atmosphere Revitalization Subsystem						Receive H_2O from WRM		Distribute process air from cabin ventilation interface	
Return moisture to the cabin	Moisture Management	Provide dry air							
Return purified air to the cabin	Provide purge air & thermal energy for regeneration	Carbon Dioxide Removal	Supply dry, high purity CO_2						
		Supply mode/operational availability status	Carbon Dioxide Conditioning & Management	Supply conditioned CO_2	Supply CO_2 for process regeneration				Overboard gas vent
Supply H_2O to WRM				Carbon Dioxide Reduction	Supply byproducts; supply mode/operational availability status	Supply mode/operational availability status			Overboard gas vent
				Supply recycle gases	Waste Product Processing & Disposal				Dispose of excess gases & inert solid waste products
				Supply H_2, mode/operational availability status	Supply H_2	Oxygen Supply & Management			
Return purified air to cabin	Supply filered & purified process air						Trace Contaminant Control	Receive filtered process air	
Return purified air to cabin							Supply filtered process air	Particulate Matter & Biocontaminant Control	Dispose of particulates & biocontaminants
									Subsystem Excess Product & Waste Management

Figure 4. A simplified interface diagram for the AR subsystem.

B. Water Recovery and Management Subsystem Interfaces

The WRM subsystem's purpose is to recycle wastewater to provide water for crew consumption, crew hygiene, and to support other water consuming systems such as electrolysis-based oxygen generators, evaporative heat exchange processes, and EVA operations. As shown by Fig. 5 the components comprising the WRM subsystem are grouped into four assemblies managing the main process fluids of the system. These assemblies are the following:

1) Water recovery from urine.
2) Water recovery from process byproducts such as urine processing brine.
3) Water purification to potable standards.
4) Potable water supply management.

In order to achieve the first function, it is necessary to treat urine so that it remains stable throughout the recovery processes. Developing a suitable chemical is the subject of development for the notional WRM subsystem. The chemical is introduced at the point of urine collection in the Waste Management System (WMS) shown by Fig. 1. This defines an interface between the WRM subsystem and the WMS. Water is recovered from the pretreated urine by a primary urine processor. The second function is achieved via a secondary processor to recover water from the concentrated brine byproduct produced by the primary processor is necessary to improve the total water recovery for exploration missions. The WRM subsystem also receives water from cabin humidity control and AR subsystem carbon dioxide reduction processes which is processed along with other waste water streams by the third component—the water purification assembly. Defining the acceptable contaminant load in humidity condensate, the carbon dioxide reduction-produced water, and other waste water streams is necessary for controlling these interfaces as excessive loading can lead to undesirable process economics for the WRM subsystem. The third assembly purifies water recovered from urine, urine brine, humidity condensate, and AR subsystem processes to produce a potable water product. A biocidal chemical is added to the potable water product to inhibit microbial growth in downstream components and storage tanks. While chemical treatment is effective, disadvantages such as long-term efficacy, human toxicity, and safety must be addressed for future exploration needs. Similar considerations must also be given to stabilizing urine for treatment.

Each of the WRM subsystem's core functions incorporates processes that may generate gaseous byproducts. Contaminants contained in these byproduct gases typically fall within SMAC limits and are candidate for venting to the habitable cabin volume. Attention must be given, however, to evaluating the impact this load has on the AR subsystem to determine whether treatment at the contaminant generation source is more economical compared to venting byproduct gases directly into the cabin.

Water Recovery and Management Subsystem	Pre-treated Urine from WMS		Humidity condensate; Water from AR CO_2 reduction; water from solid waste; sample return from EM	Distribution from Potable Water Make-up Supply
Contaminants to the cabin environment	**Water Recovery from Urine**	Byproduct Brine from Urine Processing		
Contaminants to the cabin environment		**Water Recovery from Waste Byproducts**	Water Extracted from Urine	
Supply sample to EM			**Water Purification to Potable Standards**	Potable water product
Distribute potable water to use points; provide water to ARS O_2 generation; supply sample to EM			Recycle water for post-purification treatment	**Potable Water Supply Management**

Figure 5. A simplified interface diagram for the WRM subsystem.

C. Environmental Monitoring Subsystem Interfaces

The EM subsystem addresses principle environmental health monitoring functions associated with cabin atmospheric quality, water quality, and airborne and surface microbiology.[26] Via monitoring, the LSS as well as the medical and environmental health communities ensure that key risks related to the cabin atmosphere, water quality, and microbial contamination. As part of the LSS, the EM subsystem monitors the cabin atmospheric composition, the airborne trace chemical contaminant load, combustion products, and potable water quality.[27, 28] The EM subsystem architecture, therefore, provides specific functions depicted by Fig. 6 that include the following:

1) Monitor the cabin atmospheric constituent partial pressures including oxygen, nitrogen, carbon dioxide, water vapor, hydrogen, and methane.
2) Monitor the cabin trace chemical contaminant load.
3) Monitor for combustion products such as carbon monoxide (CO), hydrogen cyanide (HCN), hydrogen chloride (HCl), and hydrogen fluoride (HF).
4) Monitor potable water quality.
5) Monitor airborne and potable water microbial contamination.

Figure 6 shows these functions require interfaces with the AR and WRM subsystems that allow for sample collection and return, particularly for water samples. Data transfer from EM components to the AR and WRM subsystems may exist as part of an autonomous LSS control approach. For instance, during a crew exercise period when oxygen consumption and carbon dioxide production are high, the EM subsystem's signal may be used to increase oxygen production and carbon dioxide removal rates to smooth major constituent partial pressure fluctuations in the cabin. Likewise, during sleep periods with low oxygen consumption and carbon dioxide production, the AR subsystem can use the EM subsystem data to match the demand. Similarly, as the EM monitors the cabin trace contaminant load, the water processing system may be able to anticipate variations in the contamination load in humidity condensate to better manage expendable resources. Likewise, monitoring the potable water quality can allow for automated compensation for additional processing to comply with specifications.

Environmental Monitoring Subsystem	Sample delivery from cabin	Sample delivery from cabin	Sample delviery from WRM	Sample delivery from cabin	Sample delivery from cabin; sample delivery from WRM
Sample return to cabin; data to cabin pressure and composition control; data to CO_2 removal and O_2 supply	**Major Cabin Atmospheric Constituent Monitoring**				
Sample return to cabin; data to cabin pressure and composition control		**Trace Cabin Atmospheric Constituent Monitoring**			
Sample return to WRM; data to WRM for control; potable water quality to crew			**Potable Water Quality Monitoring**		
Sample return to cabin; data to vehicle emergency response				**Cabin Atmospheric Combustion Product Monitoring**	
Sample return to cabin; sample return to WRM; data to the vehicle					**Airborne and Water Microbial Monitoring**

Figure 6. A simplified interface diagram for the EM subsystem.

IV. Interfaces with Supporting Infrastructure

Important interfaces for the exploration LSS include electrical power, avionics and software, thermal control, and structures. These are important infrastructure support areas for the LSS and all vehicle systems. Resource allocations for each technical area can dictate the LSS capabilities and influence the system's design. The following summarizes aspects of these technical interfaces as they relate to the exploration LSS.

A. Electrical Power

The electrical power interface is described by the Mars Design Reference Mission 5.0 to be 120 VDC. This power voltage is used aboard the ISS and, therefore, developmental work is being conducted using a 120 VDC source with voltage conditioning at the assembly and component levels as needed. The total power available is 22 kW; however, details regarding the LSS allocation are not yet specified.[29]

B. Avionics and Software

Avionics and software are necessary for the LSS to function properly. Information and insight for the crew and mission controllers to monitor the LSS and interfaces for the crew to adjust to mission needs are vital. The avionics and software architecture necessary for exploration missions is envisioned to possess standardized capabilities and interfaces that can be tailored for specific missions and vehicle platforms within a capability-driven exploration mis-

sion framework.[30] The software is envisioned to be open source and reconfigurable to take advantage of improvement in the space flight avionics and software technical area.[31] The avionics network is envisioned to be based on an Ethernet "backbone" to accommodate large data volumes and allow for commercial-off-the-shelf hardware and software products to be used.[32] The exploration LSS will use the envisioned avionics and software architectures currently under development, incorporate autonomous mission operations approaches into the software, and conduct hardware-software integration at the earliest system development maturity possible. Developing the early software architecture is key to future mission success and avoiding excessive complexity.[33]

C. Thermal Control

The LSS consists of components that will produce excess thermal energy. This energy is handled both directly and indirectly via different cooling strategies. Direct liquid cooling via heat exchangers and cold plates as well is indirect cooling by thermal energy dispersion into the cabin environment are options. Ultimately the excess thermal energy is either recovered for re-use in LSS processes or rejected to space via radiators. The methods and specific interfaces for thermal control constitute a not yet defined trade space for the LSS equipment architecture and physical layout.

D. Structural Interfaces for Maintainability

An LSS suitable for a journey to Mars and back must enable in-flight maintenance and reduce the need to store large quantities of spare parts. In-flight maintenance is necessary because the on-orbit replaceable unit (ORU) logistics and ground-based maintenance depot developed for the ISS is unsuitable for deep space exploration missions. The structural interfaces between the LSS and the habitat must not only accommodate launch and transportation loads but also must enable the crew to access components and limited life items for routine and unscheduled maintenance. An open physical layout that enables in-flight maintainability at an appropriate component level is required. By studying component replacement and maintenance aboard the ISS, the exploration LSS architecture can gain insight regarding what types of components require the most frequent maintenance. A physical layout and equipment packaging design that enables in-flight maintenance can result from this insight. As well, a targeted effort to improve component reliability can be developed. Through these efforts, a strategy for an in-flight logistics and maintainability model can be developed. An initial step is developing an LSS assembly- and component-level layout with attention to structural interfaces that allow easy access to components for repair and replacement.

E. Considerations for Component Commonality

Identifying and defining common aspects among interfaces is essential to accommodating LSS equipment components and assemblies developed by different equipment suppliers and international partners. This will enable a hassle free integration without the need to reworks or modifications to the original subsystem. Electrical power and avionics interfaces are two common technical areas discussed above. It was noted previously that the Mars Design Reference Mission assumes a 120 VDC electrical power distribution system for a deep space habitat. This is a legacy interface since the ISS U.S. Segment uses a 120 VDC electrical power distribution bus. The avionics interfaces in general and data interfaces in particular are more complicated and deserve in depth study. To this end, a team at NASA is considering a modular avionics architecture that includes the data interface. The team is currently developing figures of merit (FOMs) to evaluate different options which include the following:

1) Affordability—addresses cost in the form of base cost, launch mass, additional development cost, etc.
2) Maintainability—addresses how simple it is to keep the system healthy, functioning, and up-to-date.
3) Interoperability—addresses how well the system interfaces with others in a manner that requires little or no knowledge of the unique characteristics of those units.
4) Performance—addresses how well the system does the job that it is intended to do.
5) Robustness—addresses how well the system mitigates, detects, and recovers from faults.
6) Scalability—addresses how easily the network of systems can be extended to include new systems.
7) Security—addresses how well the system prevents unauthorized actions.

These FOMs offer detail for the broader FOMs for the Mars Design Reference Mission which include safety and mission success, effectiveness, and affordability.[34] It is anticipated that this type of developmental focus will be extended to other exploration technology development areas to identify a common set of components, for example avionics cards, sensors, valves, pumps and other equipment items that can play key roles in developing the maintainability philosophy for the future LSS. Even though the current emphasis is on LSS, no doubt that these studies will be extended to other spacecraft systems as well.

V. System Resource Allocations

Early in the mission development cycle the LSS resource allocations for mass, electrical power, volume, thermal control, data rates, and many other technical areas are not yet specified. An assessment of a deep space habitat describes a strategy for a 1000-day mission by six crewmembers that provides 11803 kg for the LSS. Within this allocation the AR subsystem is allocated 1848 kg and the WRM 5971 kg. Under a more aggressive strategy to reduce mass, the LSS mass allocation is 9114 kg with the AR subsystem mass of 1651 kg and a WRM mass of 3687 kg. The consumables for the LSS are allocated 1373 kg under the primary strategy and 1345 kg under the aggressive strategy.[35]

VI. Preliminary System Hazards Summary

A preliminary review of the notional LSS indicates hazards similar to those associated with the ISS LSS. Hazardous accumulation of contaminants, hazardous fluids, combustible gases, high temperatures and pressures, and cabin atmospheric leakage paths to space vacuum are evident.

Among the AR subsystem hazards, addressing combustible gas leakage from oxygen generation and carbon dioxide reduction equipment must be addressed and appropriate controls implemented. As well, materials of construction used in the oxygen generation assembly must be compatible with high purity oxygen as well as high purity hydrogen. Components within the trace contaminant control and carbon dioxide assemblies operate at temperatures ranging from 200 °C to 400 °C and some carbon dioxide reduction processes operate above 500 °C. Therefore, it is necessary to prevent thermal runaway and also prevent crew contact with hot surfaces and process gas streams.

Hazards within the WRM subsystem are associated with chemicals used for urine stabilization and potable water antimicrobial treatment. The low pH required for urine stabilization to prevent precipitation presents a hazard to the crew and limits the life of the wetted components. This chemical is also a corrosive acid and some formulations have carcinogenic properties. Due to the hazardous nature of urine pretreatment chemical and the pretreated urine and, likewise, urine brine, special care must be taken to properly contain this fluid throughout all parts of the process, including during maintenance.

Likewise, the long-term efficacy, human toxicity, and safety precautions necessary for potable water antimicrobial treatment must be considered. Iodine poses a health risk at large doses. This is mitigated by removing the iodine at the point of use. Work is being done to eliminate this hazard by choosing an antimicrobial chemical that can perform its function at levels that are safe to ingest while maintaining good efficacy.

Finally, inherent to any water system is the hazard posed by the large quantities of water in microgravity. Without a significant gravity vector, a water leak could present a suffocation/drowning hazard to the crew. Large quantities of water can also damage electrical equipment.

VII. Conclusion

The general features and guiding functional requirements for a notional LSS that is suited for meeting the challenges of long duration missions of a capability-driven space exploration framework were presented. The architecture was assessed relative to top-level interfaces at the system and subsystem levels. The interfaces with supporting infrastructure were presented. Among the most challenging is the need for an early, open source software architecture that incorporates autonomous mission control features. The LSS physical layout and structural interfaces must also enable easy access to components for in-flight maintenance. An early hazard analysis indicates hazards similar to those associated with the LSS aboard the ISS.

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Bibliography

The following documentation supplements the requirements and guidance found in the NASA Space Flight Human System Standard, the Human Integration Design Handbook, and the referenced documents.

Parker, J.F. and West, V.R., Bioastronautics Data Book, NASA SP-3006, 1973.

Wieland, P.O., Designing for Human Presence in Space, NASA RP-1324, 1994.

Wieland, P.O., Living Together in Space: The Design and Operation of the Life Support Systems on the International Space Station, NASA/TM-1998-206956, Vol. I, January 1998.

Perry, J.L., Elements of Spacecraft Cabin Air Quality Control Design, NASA/TP-1998-207978, May 1998.

James, J.T., “Airborne Dust in Space Vehicles and Habitats,” SAE 2006-01-2152, *SAE 36th International Conference on Environmental Systems,* Norfolk, Virginia, 2006.

James, J.T., “The Headache of Carbon Dioxide Exposures,” SAE 2007-01-3218, *SAE 37th International Conference on Environmental Systems,* Chicago, Illinois, 2007.

James, J.T., “Air Quality Standards for Space Vehicles and Habitats,” SAE 2008-01-2125, *SAE 38th International Conference on Environmental Systems,* San Francisco, California, 2008.

McCoy, J.T. and James, J.T., “Water Quality Standards for Space Vehicles and Habitats,” SAE 2008-01-2196, *SAE 38th International Conference on Environmental Systems,* San Francisco, California, 2008.

James, J.T., “A History of Space Toxicology Mishaps: Lessons Learned and Risk Management,” SAE 2009-01-2591, *SAE 39th International Conference on Environmental Systems,* Savannah, Georgia, 2009.

Perry, J.L., “A Design Basis for Spacecraft Cabin Trace Contaminant Control,” SAE 2009-01-2592, *SAE 39th International Conference on Environmental Systems,* Savannah, Georgia, 2009.

Perry, J.L., and Kayatin, M.J., Trace Contaminant Control Design Considerations for Enabling Exploration Missions, ICES 2015-108, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

Life Support Baseline Values and Assumptions Document, NASA/TP-2015-218570, March 2015.

References

[1]National Space Policy of the United States of America, June 28, 2010, p. 11.

[2]Voyages—Charting the Course for Sustainable Human Space Exploration, NP-2011-06-395-LaRC, National Aeronautics and Space Administration, 2011, p. 2.

[3]Human Exploration of Mars Design Reference Architecture 5.0, NASA-SP-2009-566, National Aeronautics and Space Administration, July 2009.

[4]NASA Strategic Plan 2014, NP-2014-01-964-HQ, National Aeronautics and Space Administration, 2014, pp. 11-13.

[5]Human Exploration of Mars Design Reference Architecture 5.0 Addendum, NASA/SP-2009-566-ADD, National Aeronautics and Space Administration, July 2009, pp. 152-153.

[6]Human Exploration of Mars Design Reference Architecture 5.0, NASA-SP-2009-566, National Aeronautics and Space Administration, July 2009, pp. 47-48.

[7]Human Exploration of Mars Design Reference Architecture 5.0 Addendum, NASA/SP-2009-566-ADD, National Aeronautics and Space Administration, July 2009, p. 65.

[8]Howard, D., Perry, J., Sargusingh, M., and Toomarian, N., “Notional Environmental Control and Life Support System Architectures for Human Exploration beyond Low-Earth Orbit,” AIAA-2015-4456, *AIAA SPACE 2015,* Pasadena, California, 2015.

[9]Hodgson, E., Converse, D., Duggan, M., and Gentry, G. “Flexible Path Environmental Control and Life Support Technology—Possible First Steps to Move Beyond LEO,” AIAA-2012-3443, *AIAA 42nd International Conference on Environmental Systems,* San Diego, CA, 2012

[10]Hodgson, E., Converse, D., Duggan, M., and Gentry, G. “Flexible Path Environmental Control and Life Support Technology—An Updated Look at Next Steps,” AIAA-2013-3409, *AIAA 43rd International Conference on Environmental Systems,* Vail, Colorado, 2013.

[11]NASA Technology Roadmaps TA 6: Human Health, Life Support, and Habitation Systems, National Aeronautics and Space Administration, 2015, pp. 4-5, 19, 21, 23-28, 51-56.

[12]NASA Space Technology Roadmaps and Priorities: Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space, National Academy Press, 2012, pp. 61, 182-203.

[13]Bagdigian, R., Gatens, R., Metcalf, J., Stephan, r., Broyan, J., Shull, S., and Macatangay, A., “National Aeronautics and Space Administration Environmental Control and Life Support Technology Development and Maturation for Exploration,” ICES-2014-19, *44th International Conference on Environmental Systems,* Tucson, Arizona, 2014.

[14]Gatens, R.L., Anderson, M.S., Broyan, J.L., Macatangay, A.V., Shull, S.A., Perry, J.L., Schneider, W.F., and Toomarian, N.B., “National Aeronautics and Space Administration Environmental Control and Life Support Technology Development and Maturation for Exploration: 2014 to 2015 Overview,” ICES-2015-111, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

[15]Schneider, W., Perry, J., Anderson, M., Broyan, J., Macatangay, A., Shull, S., Gatens, R., and Toomarian, N., “NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2015 to 2016 Overview,” ICES-2016-40, *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.

[16]NASA Space Flight Program and Project Management Requirements, NPR 7120.5E, August 14, 2012, pp. 19-33.

[17]Human Exploration of Mars Design Reference Architecture 5.0 Addendum #2, NASA-SP-2009-566-ADD2, National Aeronautics and Space Administration, March 2014, pp. 368-369.

[18]NASA Space Flight Human System Standard, Vol. 2, NASA-STD-3001, NASA, Washington, DC, January 10, 2011, pp. 26-45.

[19]Human Integration Design Handbook, NASA/SP-2010-3407, January 27, 2010, pp. 314-370.

[20]James, J.T., Spacecraft Maximum Allowable Concentrations for Airborne Contaminants, JSC 20584, NASA Johnson Space Center, Houston, Texas, November 2008.

[21]James, J.T. and McCoy, J.T., Spacecraft Water Exposure Guidelines, JSC 63414, NASA Johnson Space Center, Houston, Texas, November 2008.

[22]James, J., "Surprising Effects of CO_2 Exposure on Decision Making," AIAA-2013-3463, *43rd International Conference on Environmental Systems,* Vail, Colorado, 2013.

[23]Recommendations for Exploration Spacecraft Internal Atmospheres: The Final Report of the NASA Exploration Atmospheres Working Group, NASA/TP-2010-216134, October 2010, p. 16.

[24]Allen, C.S., Burnett, R., Charles, J., Cucinotta, F., Fullerton, R., Goodman, J.R., Griffith, A.D., Kosmo, J.J., Perchonok, M., Railsback, J., Rajulu, S., Stilwell, D., Thomas, G., Tri, T., Joshi, J., Wheeler, R., Rudisill, M., Wilson, J., Mueller, A., and Simmons, A., Guidelines and Capabilities for Designing Human Missions, NASA/TM-2003-210785, 2003.

[25]Constellation Program Human-Systems Integration Requirements, CxP 70024, March 2008.

[26]Macatangay, A.V., "An Assessment of Environmental Health Needs," AIAA 2013-3465, *AIAA 43rd International Conference on Environmental Systems,* Vail, Colorado, 2013, pp. 3, 7-10, 12-15.

[27]Jan, D.L., "Environmental Monitoring as Part of Life Support for the Crew Habitat for Lunar and Mars Missions," AIAA 2010-6092, *AIAA 40th International Conference on Environmental Systems,* Barcelona, Spain, 2010.

[28]Jan, D.L. and Newton, R., "Environmental Monitoring as Part of Life Support: Deep Space Exploration," AIAA 2012-3433, *AIAA 42nd International Conference on Environmental Systems,* San Diego, California, 2012.

[29]Human Exploration of Mars Design Reference Architecture 5.0 Addendum #2, NASA-SP-2009-566-ADD2, March 2014, pp. 367-371.

[30]Goforth, M.B., Ratliff, J.E., Hames, K.L., Vitalpur, S.V., "Avionics Architectures for Exploration: Building a Better Approach for Human Spaceflight Avionics," AIAA 2014-1604, *AIAA SpaceOps 2014 Conference*, Pasadena, California, 2014, pp. 1, 15.

[31]Krupiarz, C., "The Road to the New Flight Software," *Ask Magazine*, Summer, 2013, pp. 33-36.

[32]NASA Study on Flight Software Complexity, 2009, p. 2.

[33]Goforth, M.B., Ratliff, J.E., Hames, K.L., Vitalpur, S.V., "Avionics Architectures for Exploration: Building a Better Approach for Human Spaceflight Avionics," AIAA 2014-1604, *AIAA SpaceOps 2014 Conference*, Pasadena, California, 2014, pp. 2.

[34]Human Exploration of Mars Design Reference Architecture 5.0, NASA-SP-2009-566, National Aeronautics and Space Administration, July 2009, pp. 45-46.

[35]Human Exploration of Mars Design Reference Architecture 5.0 Addendum #2, NASA-SP-2009-566-ADD2, March 2014, p. 369.